25.2 Color and Vision

The energy of light explains how different colors are physically different. But it doesn't explain how we *see* colors. How does the human eye see color? The answer to this question also helps explain why TVs can make virtually all colors by combining only three colors!

The human eye

Photoreceptors Light enters your eye through the lens and then lands on the retina. On the surface of the retina are light-sensitive cells called **photoreceptors** (Figure 25.7). When light hits a photoreceptor cell, the cell releases a chemical signal that travels along the optic nerve to the brain. In the brain, the signal is translated into a perception of color.

Cone cells respond to color Our eyes have two types of photoreceptors, called *cones* and *rods*. Cones (or cone cells) respond to color (Figure 25.7). There are three types of cone cells. One responds best to low-energy (red) light. Another responds best to medium-energy (green) light. The third type responds best to higher-energy (blue) light.

Rod cells respond to light intensity The second type of photoreceptors are rods (or rod cells). Rods respond to differences in light intensity, but not color (Figure 25.7). Rod cells "see" black, white, and shades of gray. However, rod cells are much more sensitive than cone cells. At night, colors seem washed out because there is not enough light for cone cells to work. When the light level is very dim, you see "black-and-white" images from your rod cells.

Cone cells detect color. Rod cells detect intensity.

Black-and-white vision is sharper than color vision A human eye has about 130 million rod cells and 7 million cone cells. Each cell contributes a "dot" to the image assembled by your brain. Because there are more rod cells, things look sharpest when there is a difference between light and dark. Black letters on a white background are easier to read than colored letters because each cone cell "colors" the signals from the surrounding rod cells. Because there are fewer cone cells, our color vision is less sharp than our black-and-white vision.

VOCABULARY

photoreceptors - light-sensitive cells on the surface of the retina.

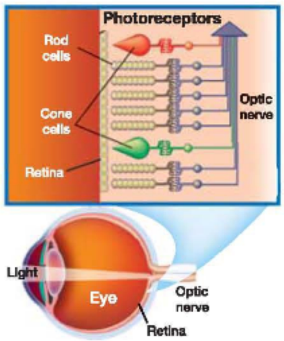


Figure 25.7: *The human eye has two types of photoreceptors—cones and rods.*

SCIENCE FACT

What Is Light Intensity?

The intensity of light is measured in watts per square meter covered. Light intensity from a small source follows an inverse square law. This means light intensity diminishes as the square of the distance increases. For example, light intensity at 2 meters from the source will be 1/4 less than it was at 1 meter. What will light intensity be at 3 meters from the source?

How we see colors

The additive color process Because there are three types of cone cells, our eyes work by adding three signals to "see" different colors. The color you "see" depends on how much energy is received by each of the three types. The brain thinks "green" when there is a strong signal from the green cone cells but no signal from the blue or red cone cells (Figure 25.8).

How we perceive color

What color would you see if light creates signals from both the green cones and the red cones? If you guessed *yellow*, you are correct. We see yellow when the brain sees yellow light, or when it gets an equally strong signal from both the red and the green cone cells at the same time. Whether the light is actually yellow, or a combination of red and green, the cones respond the same way and we perceive yellow. If the red signal is stronger than the green signal, we see orange (Figure 25.9). If all three cones send an equal signal to the brain, we see white.

Two ways to see a color The human eye can be "tricked" into seeing any color by adding different percentages of red, green, and blue. For example, an equal mix of red and green light looks yellow. However, *the light itself is still red and green!* The mix of red and green creates the same response in your cone cells as does true yellow light.

Do animals see colors? There is much to be learned about color vision in the animal kingdom. To the best of our knowledge, primates (such as chimpanzees and gorillas) are the only animals with three-color vision similar to that of humans. Some birds, fish, and insects can see ultraviolet light, which humans cannot see. Dogs and cats are thought to have weak color vision due to having only two types of cone cells and a lower proportion of them compared to rod cells. Although both octopi and squid can change their body color better than any other animal, scientists believe that most species cannot see color.

Color signals from only the green cones tell the brain the leaf is green.

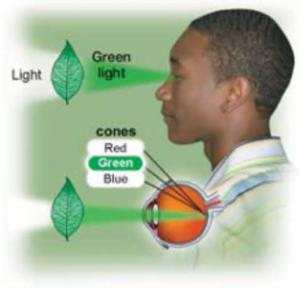


Figure 25.8: *If the brain gets a signal from only the green cones, we see green.*

A strong signal from the red cones and a weaker signal from the green cones tell the brain the fruit is orange.

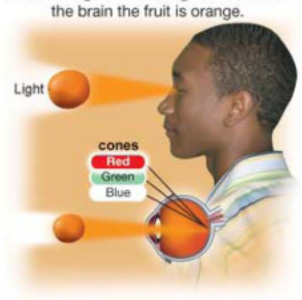


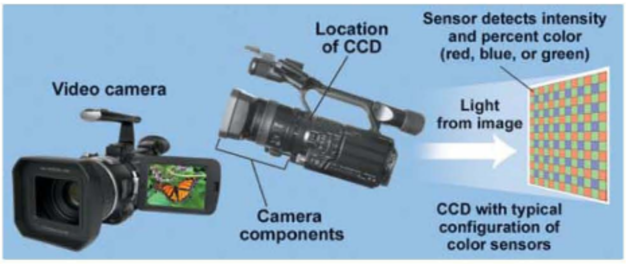
Figure 25.9: *If there is a strong red signal and a weak green signal, we see orange.*

Making an RGB color image

The RGB color process Color images in TVs and computers are based on the **RGB color model**. RGB stands for red, green, and blue. If you look at a TV screen with a magnifying glass, you will see thousands of tiny red, green, and blue **pixels** (Figure 25.10). A television makes different colors by lighting red, green, and blue pixels to different percentages. For example, a light brown tone is about 50 percent red, 33 percent green, and 17 percent blue. A computer monitor works the same way.

Pixels make up images TVs, digital cameras, and computers make images from thousands of pixels. An ordinary TV picture is 640 pixels wide × 480 pixels high, for a total of 307,200 pixels. A high-definition picture looks sharper because it contains more pixels. In the 720p format, HDTV images are 1,280 pixels wide × 720 pixels high, for a total of 921,600 pixels. This is three times as sharp as a standard TV image.

How video cameras create color images Like the rods and cones in your retina, a video camera has tiny light sensors on a small chip called a CCD (charge-coupled device). There are three sensors for each pixel of the recorded image: red, green, and blue. In HDTV, that means each recorded image contains 921,600 × 3 = 2,764,800 numbers. To create the illusion of motion, the camera records 30 images per second. In terms of data, the HDTV movie you watch represents 2,764,800 × 30, or about 83 million numbers every second.



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RGB color model - a model for tricking the eye into seeing almost any color by mixing proportions of red, green, and blue light.

pixel - a single dot that forms part of an image made of many dots.

Figure 25.10: *A television makes colors using tiny glowing dots of red, green, and blue.*

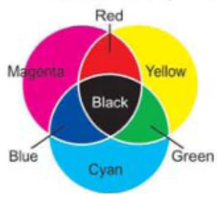
How objects appear to be different colors

What gives objects their color? Your eye creates a sense of color by responding to red, green, and blue light. You don't see objects in their own light; you see them in reflected light. A blue shirt looks blue because it *reflects blue light into your eyes* (Figure 25.11). However, the shirt did not *make* the blue light. The color blue is not *in* the cloth. The blue light you see is blue light mixed into white light that shines on the cloth. You see blue because the other colors in white light have been subtracted out (Figure 25.12).

Figure 25.11: *Why is a blue shirt blue?*

The subtractive color process Colored fabrics and paints get color from a *subtractive color process*. Chemicals known as *pigments* in dyes and paints absorb some colors and reflect other colors. Pigments work by taking away colors from white light, which is a mixture of all the colors. The shades in between red, blue, and green happen when small amounts of other colors are reflected. For example, a magenta shirt reflects blue and green light.

The Subtractive Primary Colors



The subtractive primary colors To make all colors by subtraction, we need three primary pigments. We need one that absorbs blue (reflects red and green). This pigment is *yellow*. We need another pigment that absorbs green (reflects red and blue). This is a pink-purple pigment called *magenta*. The third pigment is *cyan*, which absorbs red (reflects green and blue). Cyan is a greenish shade of light blue. Magenta, yellow, and cyan are the three *subtractive primary colors* (see the illustration above). Different proportions of the three subtractive primary colors change the amount of reflected red, green, and blue light.

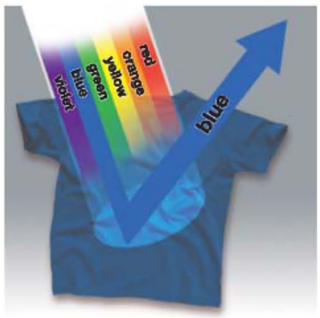


Figure 25.12: *The pigments in a blue cloth absorb all colors except blue. You see blue because blue light is reflected to your eyes.*

How the quality of white light affects what we see A blue shirt won't look blue in red light. It will look *black*! The subtractive color model assumes a painted or dyed surface is seen in white *sunlight* that contains a precise mix of colors. If the "white" has a different mix than sunlight, colors don't look right. This is why home videos made under fluorescent lights often look greenish. The white from fluorescent lights has a slightly different mix of colors than the white from sunlight.

The CMYK color process

A subtractive color process The subtractive color process is often called the **CMYK color process** for the four pigments it uses. CMYK stands for cyan, magenta, yellow, and black. The letter K stands for black because the letter B is used for the color blue in RGB. Color printers and photographs use CMYK.

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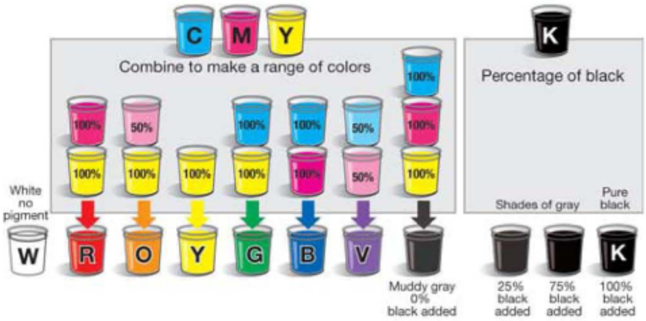
CMYK color process - the subtractive color process using cyan, magenta, yellow, and black to create colors in reflected light.



CMYK are pigments The three pigments—cyan, magenta, and yellow—combine in different proportions to make any color of reflected light. Figure 25.13 shows how CMYK pigments make green. Theoretically, mixing cyan, magenta, and yellow should make black, but in reality the result is only a muddy gray. This is why a fourth color, pure black, is included in the CMYK process.

To make	Mix	Because (White light)
Red	Magenta and yellow	Magenta absorbs green Yellow absorbs blue Red gets reflected
Blue	Magenta and cyan	Magenta absorbs green Cyan absorbs red Blue gets reflected
Green	Cyan and yellow	Cyan absorbs red Yellow absorbs blue Green gets reflected

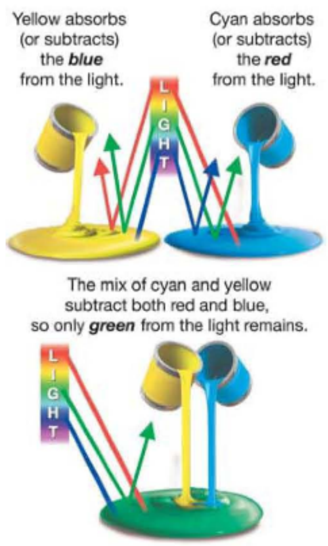


Figure 25.13: *Creating the color green using cyan and yellow paints.*

Why plants are green

Light is necessary for photosynthesis

Plants absorb energy from light and convert it to chemical energy in the form of sugar. This process is called *photosynthesis*. The vertical (*y*) axis of the graph in Figure 25.14 shows the percentage of different colors of light that are absorbed by a plant. The *x*-axis shows the colors of light. The graph line shows how much and which colors of visible light are absorbed by plants. Based on this graph, can you explain why plants look green?

Why most plants are green

The important molecule that absorbs light in a plant is called *chlorophyll*. There are several forms of chlorophyll. They absorb mostly blue and red light, and reflect green light. This is why most plants look green. The graph in Figure 25.14 shows that plants absorb red and blue light to grow. A plant will die if placed under only green light!

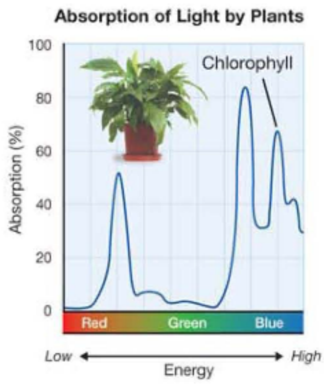


Figure 25.14: *Plants absorb energy from light. The plant pigment chlorophyll absorbs red and blue light, and reflects green light. This is why plants look green.*

Plants reflect some light to keep cool

Why don't plants absorb all colors of light? The reason is the same reason you wear light-colored clothes when it's hot outside. Like you, plants must reflect some light to avoid absorbing too much energy and overheating. Plants use visible light because the energy is just enough to change certain chemical bonds, but not enough to completely break them. Ultraviolet light has more energy but would break chemical bonds. Infrared light has too little energy to change chemical bonds.

Why leaves change color

The leaves of some plants, such as sugar maple trees, turn brilliant red or gold in the fall. Chlorophyll masks other plant pigments during the spring and summer. In the fall, when photosynthesis slows down, chlorophyll breaks down and red, orange, and yellow pigments in the leaves are revealed.

CHALLENGE

What About Red Plants?

All plants that use sunlight to grow have chlorophyll, but some do not look green. Come up with a hypothesis to explain this observation.

25.2 Section Review

1. If humans have only three types of color photoreceptors, how can we see so many different colors?
2. Why is it easier to read black text on a white background than to read green text, or text of any light color, on a white background?
3. Why might it be a good idea to put a light in your clothes closet? (Hint: What kind of vision do we have in dim light?)
4. How does the human eye detect the color magenta?
5. Do you think this text book was printed using the CMYK color process or the RGB color process? Explain your answer.
6. If you were going to design the lighting for a play, would you need to understand the CMYK color process, the RGB color process, or both? Explain your answer.
7. Suppose you have cyan, magenta, yellow, and black paint. Which colors would you mix to get blue?
8. How is a CCD like the retina in a human eye?
9. How is the color black produced in the CMYK color process? How does this differ from the RGB color process?
10. A red shirt appears red because:
    a. the shirt reflects red light.
    b. the shirt absorbs red light.
    c. the shirt emits green and blue light.
    d. the shirt reflects magenta and blue light.
11. Explain the role of chlorophyll in plants. How does this pigment molecule help plants survive?
12. What would happen if you tried to grow a green plant in pure green light? Would the plant live? Explain your answer.
13. Propose an explanation for how the top image in Figure 25.15 is related to the four images below it.

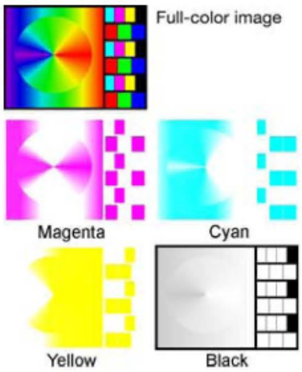


Figure 25.15: *Question 14.*

CHALLENGE

Pictures from Dots

A color printer, such as an inkjet printer, makes color images by printing small dots. If there were only four dots per inch, your eye would see the individual dots instead of the picture the dots are supposed to make. How many dots must there be (per inch) to trick the eye into seeing a smooth image? How many dots per inch do printers in your home or school use?